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The impact of climate warming and crop management on phenology of sunflower-based cropping systems in Punjab, Pakistan

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ABSTRACT

Understanding the effects of warming trends, genetics, and management on crop phenology is crucial for adaptation against the increasing trend in temperature in the upcoming decades. The goal of this research was to quantify the impact of historic climate warming and management on sunflower phenology (stages and phases). In this project, spring and fall sunflower phenology and daily weather data were obtained for 20 locations in Punjab, Pakistan. We investigated the impact of thermal trend on the phenological stages and phase duration for spring and fall sunflower from 1980 to 2016. The results showed that the mean temperature increased by 0.9 and 0.8 °C decade^{-1} for spring and fall, respectively. The observed phenological stages such as sowing, emergence, anthesis, and maturity dates were earlier for spring by an average of 6.6, 6.3, 3.8, and 2.2 days decade^{-1}and delayed for fall by an average of 5.7, 5.4, 3.1, and 1.8 days decade^{-1}. The observed sowing to anthesis, anthesis to maturity, and sowing to maturity phases were reduced by an average of 2.8, 1.6 and 4.4 days decade^{-1}for spring and 2.5, 1.2, and 3.8 days decade^{-1} for fall. The changes in phenology of sunflower for spring and fall were highly correlated with the enhancement in warming trend during 1980–2016. The CSM-CROPGRO-Sunflower model using standard hybrids for all sites and years showed that the simulated phenology had accelerated due to the change in climate and the simulated phenological dates were earlier than the observed dates. These results indicate that earlier sowing dates for spring, delayed sowing dates for fall, and shifts of varieties that require elevated total growing degree days for the duration of 1980 to 2016 have somewhat mitigated the adverse impact of climate warming on spring- and fall-grown sunflower phenology for ensuring sustainable productivity and ensuring food security.

1. Introduction

Edible oils are an important component of the human dietary needs. Pakistan is characterized as deficient in edible oil production and imports costs upon US$ 2.71 billion (Govt. of Pakistan, 2017). Sunflower ranks third with a 9.19% share in domestic edible oil production followed by cotton and rapeseed/mustard (Govt. of Pakistan, 2017; Amin et al., 2017a; Nasim et al., 2018). Sunflower seeds contain 40-50% oil and 40% digestible protein (Abbas et al., 2017a; Amin et al., 2018). Although sunflower is a crop of temperate regions, it has been grown successfully in a broad range of environmental conditions ranging from humid to semi-arid and arid climates.

Punjab is an important agricultural region with 20.63 million ha of land under cultivation, which is approximately 26% of the land area of Pakistan (Government of Pakistan, 2012; Nasim et al., 2016a; Noreen et al., 2016). The Punjab is divided into two regions, central Punjab, with a mild climate and a mean temperature that ranges from 10.5 to 24.4 °C and average rainfall between300 and 600 mm, and southern

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Table 1
Sunflower cultivars at all locations.

Site Name	Cultivars
Sialkot	Super-25, DK4045, Hysun-777, NKR-72, Peredovic-2
Lahore	Engro-9704, SF-187, PSF-025, DK-3849, Mayak
Okara	FH-75, Super-25, Cheeta, T-562, SF-046, B-37, IS-894
Gujranwala	Beimisal-205, SH-3322, NK-1435, SF-049, M-14, P-64A93
Hafizabad	PARC-92, NK-212, Hysun-39, FH-331, Aritar-93
Sheikhupura	SMH-976, SF-177, PNSF-1, DK-3176, Suncom-1, S-278
Nankana Sahib	NK-265, HS-341, XF-263, FMC-3849, VINMK-8931
Sargodha	SF-287, NK-212, Parsun-12, Gimsun-435, SB-212, Hysun-38
Faisalabad	PI-6480, PARSUN-1, P-9706, Gimsun-476, Suncom-110
Jhang	SMH-095, Hysun-39, Award-3, SF-574, Pioneer-6354
Sahiwal	PARSUN-3, NKS-278, M-3255, Gimsun-7741, SMH-13
Khanewal	Gimsun-456, Hysun-36, Gulshan-98, Allsstarm, HO-1
Multan	Gimsun-6741, Hysun-33, ORI-3B, G-2, Turkish-473, VK-654
Vehari	Pioneer-6470, Gimsun-226, ORI-27B, Nusun-652, HOI-2
Muzaffargarh	NK-274, CM-628, LG-5380, Gimsun-406, VNIMK-8931
Lodhran	Sun-535, PARSUN-2, Nusun-5501, HS-6, Inra-4701
Pakpattan	G-101, Pioneer-6532, Pioneer-3321, FH-330, SMT-1
Bahawalpur	CRN-1435, P-9705, Hysun-33, N4HM-35, SF-187, FH-337
Bahawalnagar	DK-4040, JH-99, DK-4327, N-4334, FH-2, DK-432
Rahim Yar Khan	Pioneer-6435, Gimsun-96, JH-94, NK-265, LM-307

Punjab, with a harsh climate and relatively high temperatures ranging from 18.5 to 31.4 °C and average rainfall of between 75 and 200 mm (Akram and Hamid, 2015; Ahmad et al., 2016; Amin et al., 2017b; Abbas et al., 2017b; Anjum et al., 2016; Ishaq and Memon, 2016).

Climate plays a fundamental role in agricultural systems, and concerns about threats and opportunities associated with climate change are gaining more attention. Noted changes include warmer day and night temperatures, variable rainfall distribution patterns, higher atmospheric CO_2, and hydrological imbalances. The General Circulation Models (IPCC et al., 2014; Reddy et al., 2002; Nasim et al., 2017) predict that global mean temperature will increase from 1.4 to 5.8 °C in the present century. The IPCC et al., 2014 noted that 2001–2010 was the hottest recorded decade and 2014 was the hottest year of the 21st century. The intensity, frequency, and duration of extreme temperatures are expected to outpace the current increase in temperature (Fahad et al.,2016a; Fahad et al.,2016b; Fahad et al.,2016c; Fahad et al., 2016d; Meehl et al., 2007). The expected trend in global warming could have a significant impact on the time of occurrence and duration of phenological phases in plants. Generally, it is projected that agriculture of arid, semi-arid, and warmer regions in general of the world are at the greatest risk of climate change (Adams et al., 1998; Ali et al., 2017; Fahad et al., 2014a; Fahad et al., 2014b; Fahad et al., 2015a; Fahad et al., 2015b). Pakistan is very vulnerable to climate change because of its arid and semi-arid climate, which are expected to show a higher increase in temperature compared to the global trends (Rasul et al., 2012; Nasim et al., 2012; Ahmad et al., 2016; Abbas et al., 2017a, b).

Optimum growth and development of sunflower occurs at a temperature range of 26–29 °C (Rondanini et al. 2006; Awais et al., 2017a; Hammad et al., 2017; Jabran et al., 2017b) and sustainable production is under the threat of climate change (Kalyar et al., 2013). In addition to crop management and genetic characteristics (Izquierdo et al., 2002; Wang et al., 2016; Awais et al., 2017b; Jabran et al., 2017a; Nasim et al., 2016a), the shift in phenology of various species has been attributed to climate change (Visser and Both, 2005; Miller-Rushing and Primack, 2008; Parmesan and Yohe, 2003; Gordo and Sanz, 2010; Agostino et al., 2012; Yang et al., 2014; Szabó et al., 2016; Jan et al., 2017; Nasim et al., 2016b). Hence, the changes in phenology over time indicate the impact of climate change and a plant's adoptive responses (Wang et al., 2014). Since, air temperature plays an important role in crop development (Ahas and Aasa, 2006; Kaleem et al., 2009; Hatfield and Prueger, 2015), an earlier occurrence of the phenological stages is expected in warmer climates due an increase in observed temperature of 0.2 °C per decade during the last three decades (Hansen et al., 2006; Ahmad et al., 2016, 2017a, b; Abbas et al., 2017a, b). The upsurge in minimum temperature has often been ignored while evaluating the impact of climate change. However, the changes in minimum temperature are more important to determine the phenology of crops (Hatfield et al., 2011; Nasim et al., 2016c; Mahmood et al., 2017). The timing of flowering and maturity are considered important traits for designing effective adaptation strategies (Forrest and Miller-Rushing, 2010; Nasim et al., 2011; Li et al., 2014). However, so far only a few studies have investigated the impact of global warming on phenology and long-term changes in phenology. These include canola (Ahmad et al., 2017a, b), sugarcane (Ahmad et al., 2016), cotton (Ahmad et al., 2017a, b; Wang et al., 2017), maize (Li et al., 2014; Wang et al., 2016; Abbas et al., 2017a, b), cherry trees (Miller-Rushing et al., 2007), and wheat (He et al., 2015). So, far there has been a lack of information about sunflower phenology. The objectives of this study were (1) to determine the spatial and temporal variability in sunflower phenology and the temperature trend from 1980 to2016 in response to climate change, (2) to use a dynamic crop growth model for separating the effects of climate warming, cultivar shift and crop management on spring and fall sunflower phenology.

2. Materials and methods

2.1. Local climate and phenology

The data regarding the observed phenological events for spring (January-June) and fall (July-November) seasons sunflower from 1980 to 2016 were obtained from the Punjab Agriculture Department (PAD) and the long-term daily weather data for 36 years for 20 selected sites were obtained from the Pakistan Metrological Department (PMD), respectively. Sowing, emergence, anthesis (50%), and physiological maturity dates (50%) were the observed phenological stages for spring and fall sunflower. Using the observed phenological stages, three phenological phases including, sowing-anthesis (S-A), anthesis-maturity (A-M), and sowing-maturity (S-M) were determined. All management practices were based on the local farming community for both spring and fall sunflower crops (Govt. of Pakistan, 2017). Old spring and fall sunflower hybrids were replaced with improved hybrids by the local farmers every five to seven years, with an average of five hybrids for the study period weather station (Table 1). This successive adoption of hybrids was associated with a higher total growing degree day requirement for the main phenological stages.

2.2. Data analysis

Linear regression was used to determine the tendencies for both observed phenological stages and phases for the spring and fall crop in relation to the mean seasonal temperature. Based on the maximum occurrence of the phenological stages for each location, the time frames for determining the thermal trends were obtained. The time frame for the growing season duration, i.e., from sowing to maturity (S-M) was counted from the earliest date of sowing to the latest maturity date during the past four decades for each location (Govt. of Pakistan, 2017). Using his approach, the measured warming trend was not dependent on the analogous variability of the phenological stages and phases. Quantified association of dates of sowing with average monthly temperature for the sowing was determined to assess whether average monthly temperature affected the sowing dates. Subsequent linear regression was applied to determine the influence of changing

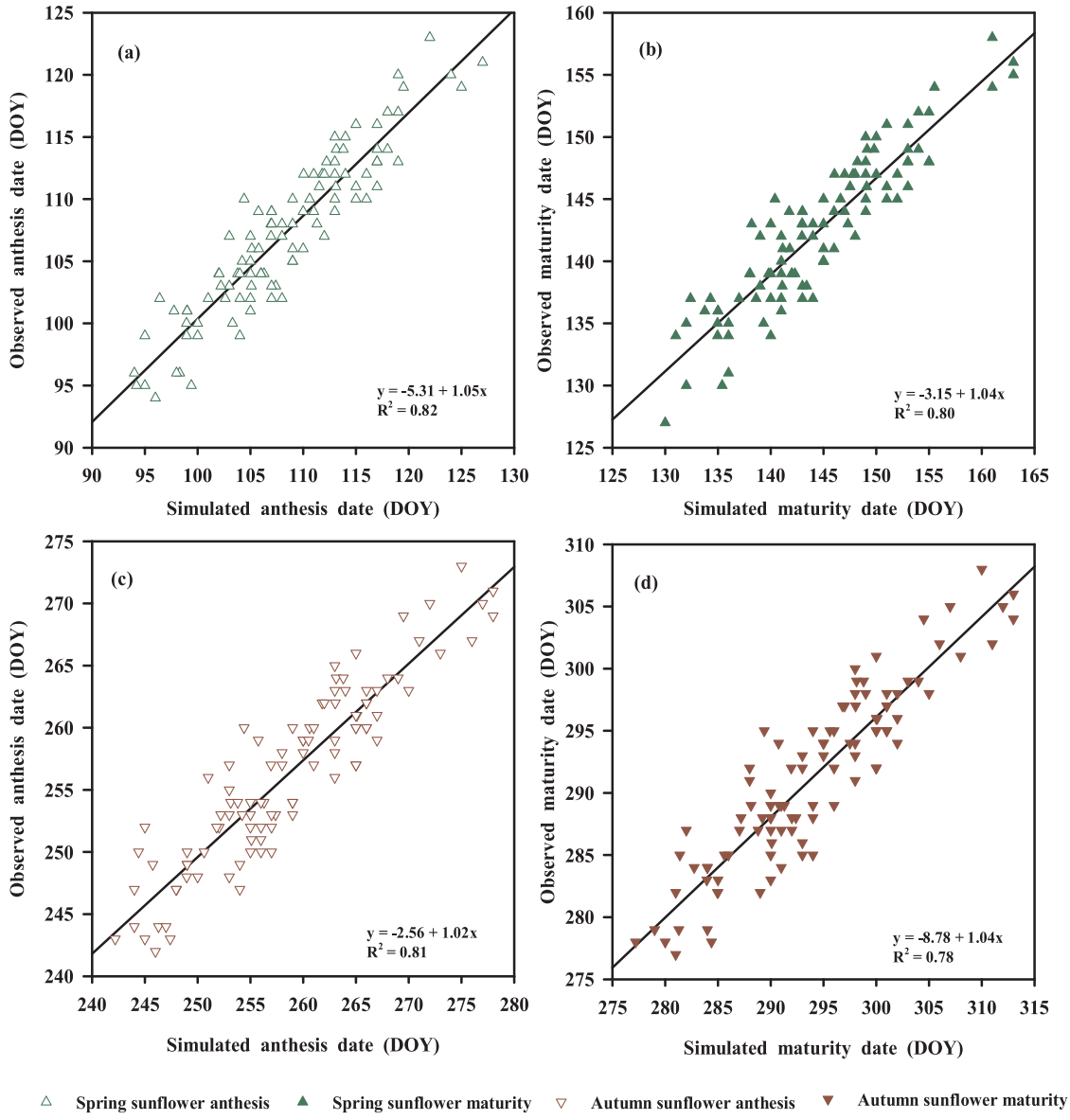

Fig. 1. Comparison of simulated and observed anthesis and maturity dates for spring (a, b; upward unfilled and filled triangles) and autumn season (c, d; downward unfilled and filled triangles) sunflower crop, respectively during 1980–1985 for 20 locations in Punjab, Pakistan.

temperature on the phenology of spring and fall sunflower.

$$OP_{nt} = a_{nt}T_{nt} + b_{nt} + \varepsilon_{nt} \quad (1)$$

In Equation 1, observed phases in farmer's fields ('DOY', day of year) or its duration in days is symbolized by 'OP_{nt}' for the corresponding nth local weather station or location in the respective t year. 'T_{nt}' represents average daily temperature in ºC during the relevant phenological stage or phase for the specific locations in year *t*. The regression coefficient (days $^{o}C^{-1}$) of phenological stage or phase responding to temperature are symbolized by the variable 'a_{nt}'. Variables 'b_{nt}' and '$\in_{nt}$' represent the intercept and error term for each particular location, respectively. The phenological stages plus phases for spring as well as fall sunflower responding to increasing temperature and crop agronomic management changes were analyzed by variable regression coefficient (a_{nt}).

2.3. Calculating growing degree days and simulating phenology with model

In the DSSATCSM-CROPGRO-Sunflower model(Jones et al., 2003; Hoogenboom et al., 2017), the phenological stages and phases for sunflower are determined based on photothermal time and the total number of photothermal units required for each developmental phase, which are hybrid specific. The accumulation of photothermal time for each phenological phase i.e., sowing-anthesis (S-A) and anthesis-maturity (A-M) is calculated with the following formula:

$$ATT = \sum_{i=1}^{n} DTT \quad (2)$$

In this equation, DTT is defined as photothermal time day^{-1} and n is the number of days for a given crop phenological phase. The crop model DSSAT uses daily weather data as input, including maximum and minimum temperatures, precipitation along with solar radiation for calculating daily growth and development rates (Jones et al., 2003).This study used the CSM-CROPGRO-Sunflower model Version 4.7 (Hoogenboom et al., 2017).

Only one cultivar and the same crop management practices were used throughout the study period. The phenological stages and phases

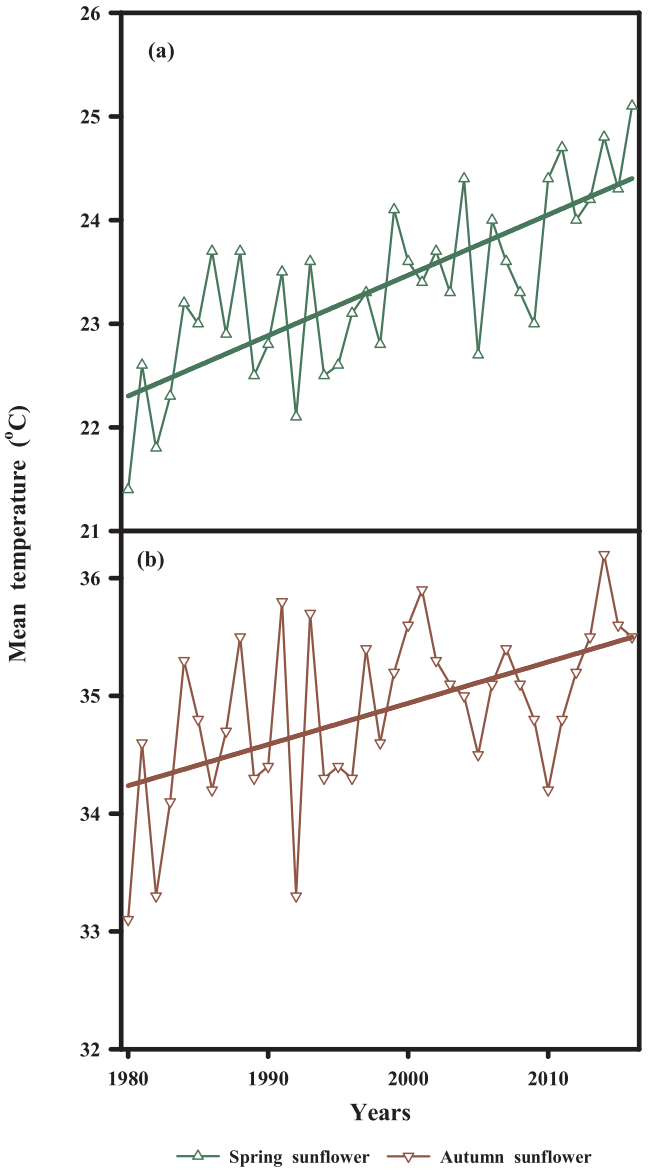

Fig. 2. Mean temperature trends in spring (a) and autumn (b) sunflower season from 1980 to 2016 in Punjab, Pakistan.

for spring and fall sunflower were predicted with CSM-CROPGRO-Sunflower to determine the effect of temperature on sunflower phenology separate from changes in technology related to crop management and sunflower hybrid adaptation. The 'A' and 'M' dates and the numbers of days from planting to maturity were simulated from 1980 to 2016 for all 20 local weather stations. A single, most dominant hybrid from 1980 to 1982 for each location was used for the calibration of the CSM-CROPGRO-Sunflower model, resulting in 10 different hybrids. Following model calibration, the observed data for spring and fall sunflower phenology from 1983 to 1985 were used for model evaluation. Then, the CSM-CROPGRO-Sunflower was used to simulate spring and fall sunflower phenological stages and phases from 1980 to 2016 based on the same hybrid and crop management practices. The effect of temperature on the simulated spring and fall sunflower phenological phases, including S-A, A-M, and S-M was assessed with linear regression using the following equation:

$$SP_{nt} = C_{nt}T_{nt} + d_{nt} + \varepsilon_{nt} \quad (3)$$

In this linear regression equation, the model-predicted phenological stages ('DOY', day of year) or the duration of the phenological phases (days) is symbolized by "SP_{nt}" for the corresponding n^{th} local weather station or location and for the relevant year 't'. 'T_{nt}' represents mean daily phenological phase temperature in ºC during the related phenological phase for a specific location. The regression coefficient (days $^{o}C^{-1}$) of phenological phase responding to the warming trend is symbolized by 'c_{nt}' variable. The variables 'd_{nt}' and '$\in_{nt}$' are the intercept and error term for every particular location, respectively. The response of the spring and fall sunflower predicted phenological phases to temperature are represented by the regression coefficient ('c_{nt}').

2.4. Growing degree days calculation for sunflower phenology

Total growing degree days (GDD) for spring and fall sunflower phenological phases, sowing-anthesis (S-A), and anthesis-maturity (A-M) were computed according to Gallagher and Biscoe (1978) by using the following equation that calculates growing degree days as a function of mean temperature above a base temperature.

$$GDD = \frac{\sum (Tmax + Tmin)}{2} - Tb \quad (4)$$

Tbase for sunflower is taken as 8 °C (Sadras and Hali, 1988).

A comparison of the model-simulated and observed phenological stages in farmers' fields, i.e., anthesis and maturity dates for 1983 to 1985 for model evaluation for the 20 study locations are shown in Fig. 1. The CSM-CROPGRO-Sunflower model performed well for all locations, as shown by the agreement between the model-predicted anthesis and physiological maturity dates and observed phenological data for anthesis and maturity for spring sunflower (slope = 1.05, $R^2 = 0.82$, $p < 0.01$; slope = 1.04, $R^2 = 0.80$, $p < 0.01$, respectively) and for fall sunflower (slope = 1.02, $R^2 = 0.81$, $p < 0.01$; slope = 1.04, $R^2 = 0.78$, $p < 0.01$, respectively) (Fig. 1).

2.5. Difference between observed and simulated phenology response to temperature

In Equation 1, variable 'a_{nt}' is a regression coefficient which represents the response of spring and fall sunflower phenology to the change in cultivar, sowing date, and temperature. However, in Equation 3, the effect of temperature on model-predicted crop phenology is considered by the 'c_{nt}' regression coefficient. If the difference between the regression coefficient (a_{nt} - c_{nt}) is negative values, this means that local farmers grew short-duration hybrids in the early or "cooler" years. If the difference between the regression coefficient is positive, this means that local farmers grew longer-duration hybrids in the later or "hotter" years. A 'paired t-test' was used to determine the significant difference ($p < 0.01$) between the regression coefficients.

3. Results

3.1. Temperature trends spring and fall growing seasons

Thermal trends were observed for duration of both spring and fall sunflower crops (Fig. 2), with an observed higher thermal trend for the spring. The change in temperature from sowing to anthesis ranged from 0.4 to 0.8 °C decade^{-1}for the spring season and from 0.2 to 0.6 °C decade^{-1} (statistically significant; $p < 0.05$) for the fall season (Fig. 3). There was also an increase in temperature for the anthesis to maturity phase, ranging from 0.5 to 1.0 °C decade^{-1} (statistically significant; $p < 0.05$) for the spring season and 0.4 to 0.9 °C decade^{-1}for the fall season

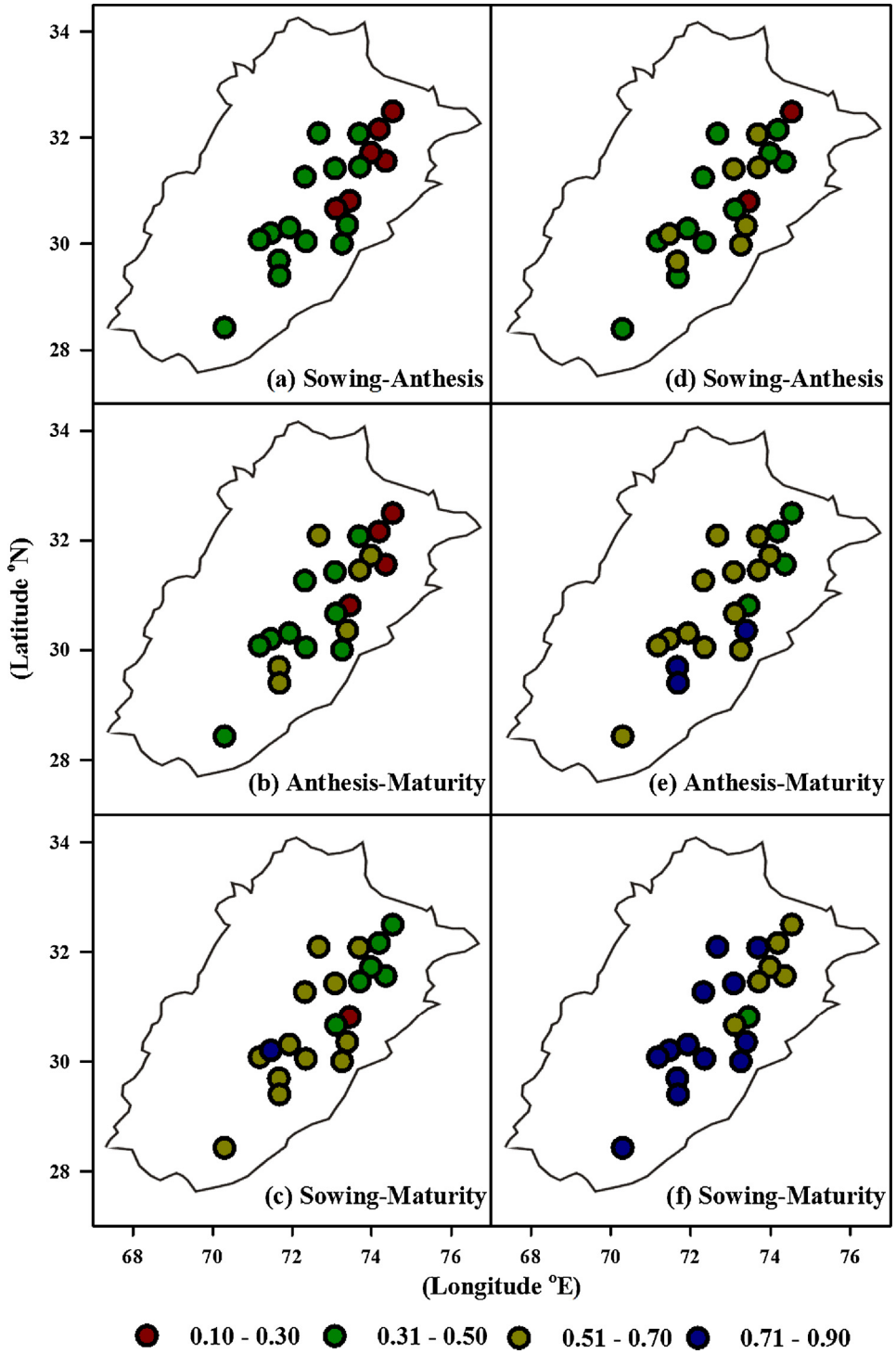

Fig. 3. Observed trends in mean temperature during the phenological phases {sowing-anthesis (a, d); anthesis-maturity (b, e) sowing-maturity (c, f)} for spring (a, b and c; left) and autumn (d, e and f; right) seasons sunflower crop from 1980 to 2016 in Punjab, Pakistan.

(statistically significant; $p < 0.05$). The change in temperature ranged from 0.6 to 1.1 °C decade^{-1} for the spring season (statistically significant; $p < 0.05$) and 0.5 to 0.9 °C decade^{-1}for the fall season (statistically significant; $p < 0.05$) for the period of sowing to maturity.

3.2. Trends in sunflower stage occurrence

Spring sunflower is normally sown in early January to end February and fall sunflower is generally sown in from beginning of July to the end of Augustin Punjab, Pakistan (Table 2). Phenology of spring and fall sunflower was affected by cultivars and sowing dates. Spring sunflower phenology stages were advanced and fall delayed with late in sowing (Supplementary Tables S1 and S2).The sowing dates for spring sunflower advanced, ranging from 3.4 to 9.3 days decade^{-1} (statistically significant for 18 locations) and on average, 6.6 days decade^{-1}, while sowing dates were delayed for fall sunflower, ranging from 2.7 to 8.4

Table 2
Average observed phenology day of year (DOY) of spring and autumn sunflower in Punjab, Pakistan during period of 1980–2016.

Location	S (DOY)	E (DOY)	A[a] (DOY)	M[b] (DOY)	S-A (days)	A-M (days)	S-M (days)
Spring							
Sialkot	42 ± 4.5	47 ± 4.4	117 ± 6.4	158 ± 4.2	75 ± 3.2	41 ± 5.3	116 ± 5.0
Lahore	39 ± 6.2	44 ± 6.1	112 ± 5.2	150 ± 4.7	73 ± 4.1	38 ± 5.1	111 ± 6.1
Okara	30 ± 3.7	35 ± 3.2	108 ± 4.3	138 ± 6.2	78 ± 5.3	30 ± 4.1	108 ± 7.5
Gujranwala	26 ± 5.2	31 ± 4.9	106 ± 5.1	137 ± 5.2	80 ± 4.9	31 ± 6.3	111 ± 4.0
Hafizabad	33 ± 8.2	38 ± 7.2	101 ± 3.5	140 ± 6.8	68 ± 2.7	39 ± 5.2	107 ± 5.3
Sheikhupura	31 ± 3.2	36 ± 2.9	103 ± 5.3	133 ± 7.2	72 ± 3.9	30 ± 5.9	102 ± 4.6
Nankana Sahib	26 ± 5.2	31 ± 5.1	100 ± 6.2	137 ± 6.0	74 ± 3.1	37 ± 4.3	111 ± 6.1
Sargodha	34 ± 4.1	39 ± 3.8	104 ± 4.3	142 ± 4.1	70 ± 5.5	38 ± 6.8	108 ± 3.9
Faisalabad	32 ± 3.5	37 ± 3.3	102 ± 5.5	145 ± 3.3	70 ± 6.2	43 ± 4.7	113 ± 5.3
Jhang	29 ± 4.2	34 ± 4.1	104 ± 3.6	139 ± 3.9	75 ± 5.1	35 ± 3.2	110 ± 6.2
Sahiwal	27 ± 4.4	31 ± 4.0	100 ± 5.3	138 ± 4.2	73 ± 6.8	38 ± 4.1	111 ± 6.5
Khanewal	24 ± 3.9	28 ± 3.5	95 ± 6.2	136 ± 5.1	71 ± 4.6	41 ± 3.2	112 ± 3.9
Multan	15 ± 2.8	19 ± 2.6	92 ± 5.9	128 ± 3.9	77 ± 3.9	36 ± 5.2	113 ± 4.4
Vehari	16 ± 3.7	20 ± 3.4	85 ± 6.1	126 ± 4.4	69 ± 4.4	41 ± 3.1	110 ± 5.2
Muzaffargarh	18 ± 5.1	22 ± 4.7	93 ± 4.4	122 ± 3.6	75 ± 7.2	29 ± 4.5	104 ± 4.3
Lodhran	16 ± 2.5	20 ± 2.0	87 ± 3.4	128 ± 3.0	71 ± 3.4	41 ± 5.0	112 ± 5.2
Pakpattan	11 ± 3.1	15 ± 2.8	80 ± 5.3	121 ± 4.9	69 ± 4.6	41 ± 6.3	110 ± 6.7
Bahawalpur	19 ± 5.6	23 ± 4.9	99 ± 4.2	128 ± 6.3	80 ± 5.1	29 ± 6.8	109 ± 4.3
Bahawalnagar	17 ± 5.4	21 ± 4.2	96 ± 4.0	125 ± 7.1	79 ± 6.7	29 ± 4.2	108 ± 4.9
Rahim Yar Khan	14 ± 4.3	18 ± 3.9	85 ± 6.2	119 ± 5.3	71 ± 5.1	34 ± 5.6	105 ± 5.6
Autumn							
Sialkot	202 ± 4.6	207 ± 4.1	275 ± 5.2	314 ± 6.1	73 ± 5.1	39 ± 3.9	112 ± 5.2
Lahore	199 ± 3.2	204 ± 2.9	270 ± 4.8	312 ± 5.5	71 ± 6.3	42 ± 4.4	113 ± 4.9
Okara	190 ± 5.1	195 ± 4.9	266 ± 6.3	305 ± 4.2	76 ± 3.7	39 ± 4.1	115 ± 7.0
Gujranwala	186 ± 2.8	191 ± 2.3	264 ± 7.2	296 ± 5.8	78 ± 5.3	32 ± 4.0	110 ± 6.8
Hafizabad	193 ± 4.1	198 ± 3.4	259 ± 4.9	298 ± 6.2	66 ± 3.6	39 ± 5.1	105 ± 5.3
Sheikhupura	191 ± 7.1	196 ± 4.1	261 ± 5.1	294 ± 4.8	70 ± 2.7	33 ± 5.5	103 ± 4.7
Nankana Sahib	186 ± 3.9	191 ± 3.6	258 ± 6.2	293 ± 3.9	72 ± 7.3	35 ± 4.8	107 ± 3.1
Sargodha	194 ± 5.2	199 ± 4.9	262 ± 5.5	296 ± 4.1	68 ± 5.7	34 ± 3.7	102 ± 3.8
Faisalabad	192 ± 4.6	197 ± 4.0	260 ± 6.0	293 ± 3.8	68 ± 4.2	33 ± 4.3	101 ± 4.7
Jhang	189 ± 3.3	194 ± 3.1	262 ± 4.4	296 ± 8.2	73 ± 3.6	34 ± 6.3	107 ± 5.2
Sahiwal	187 ± 5.2	192 ± 5.0	258 ± 3.9	290 ± 7.0	71 ± 7.2	32 ± 5.5	103 ± 4.8
Khanewal	184 ± 3.8	189 ± 3.5	253 ± 7.1	292 ± 4.5	69 ± 5.2	39 ± 3.9	108 ± 3.6
Multan	185 ± 3.1	190 ± 2.8	260 ± 6.2	290 ± 3.2	75 ± 4.3	30 ± 7.6	105 ± 7.4
Vehari	186 ± 4.0	191 ± 3.9	253 ± 5.8	288 ± 5.1	67 ± 6.2	35 ± 5.0	102 ± 4.6
Muzaffargarh	188 ± 5.4	193 ± 5.1	261 ± 3.9	297 ± 4.8	73 ± 4.9	36 ± 4.4	109 ± 3.9
Lodhran	186 ± 2.9	191 ± 2.6	255 ± 5.9	293 ± 3.9	69 ± 3.6	38 ± 3.6	107 ± 5.6
Pakpattan	181 ± 3.7	186 ± 3.5	248 ± 4.1	289 ± 5.2	67 ± 2.7	41 ± 6.1	108 ± 5.0
Bahawalpur	189 ± 4.1	194 ± 3.8	267 ± 5.0	295 ± 6.3	78 ± 3.1	28 ± 5.8	106 ± 4.2
Bahawalnagar	187 ± 3.1	192 ± 2.9	264 ± 4.1	290 ± 5.7	77 ± 3.6	26 ± 4.6	103 ± 3.7
Rahim Yar Khan	186 ± 5.7	191 ± 5.4	255 ± 3.7	292 ± 4.9	69 ± 3.9	37 ± 4.0	106 ± 4.9

[a] 50% Anthesis.
[b] 50% Physiological maturity.

days decade^{-1} (statistically significant for 16 locations) and by an average of 5.7 days decade^{-1} (Fig. 4). A similar trend in emergence dates was observed for the spring and fall sowing dates because emergence dates were directly linked to the sowing dates (Fig. 5). The advance in emergence dates for spring sunflower ranged from 3.2 to 8.9 days decade^{-1} (statistically significant for 17 locations), with an average of 6.3 days decade^{-1}. The emergence dates **for fall** sunflower were delayed from 2.5 to 8.1 days decade^{-1} (statistically significant for 15 locations), with an average of 5.4 days decade^{-1}. Flowering for spring sunflower usually occurred from the end March to the end April and for fall sunflower from the beginning of September to the beginning of October (Table 2). The anthesis dates were advanced ranging from 1.6 to 5.9 days decade^{-1} (statistically significant for 19 locations) with average of 3.8 days decade^{-1} for spring sunflower and from 1.4 to 4.5 days decade^{-1} (statistically significant for 17 locations) having an average of 3.1 days decade^{-1} for fall sunflower. Physiological maturity for spring sunflower usually occurred from early May to the end of June and for fall sunflower from early October to end-November. Physiological maturity of spring sunflower was advanced ranging from 1.0 to 4.3 days decade^{-1} (statistically significant for 16 locations) having average value of 2.2 days decade^{-1} and for fall sunflower ranged from 0.8 to 2.7 days decade^{-1} (statistically significant for 16 locations) with an average value of 1.8 days decade^{-1}.

3.3. Trends in sunflower phase duration

The phase duration from sowing to anthesis for spring was reduced from 1.3 to 4.5 days decade^{-1} (statistically significant for 15 locations) with average value of 2.8 days decade^{-1}and for fall sunflower reduction ranged from 1.2 to 3.9 days decade^{-1} (statistically significant for 14 locations), having an average of 2.5 days decade^{-1} (Fig. 6). The phase duration from anthesis to maturity for spring sunflower was shortened and ranged from 1.1 to 2.4 days decade^{-1} (statistically significant for 18 locations), by an average of 1.6 days decade^{-1} and for fall sunflower ranged from 0.6 to 1.9 days decade^{-1} (statistically significant for 17 locations) with an average value of 1.2 days decade^{-1}. Due to shorter sowing to anthesis and anthesis to maturity phases, the phase duration from sowing to maturity was also reduced. Sowing to maturity phase

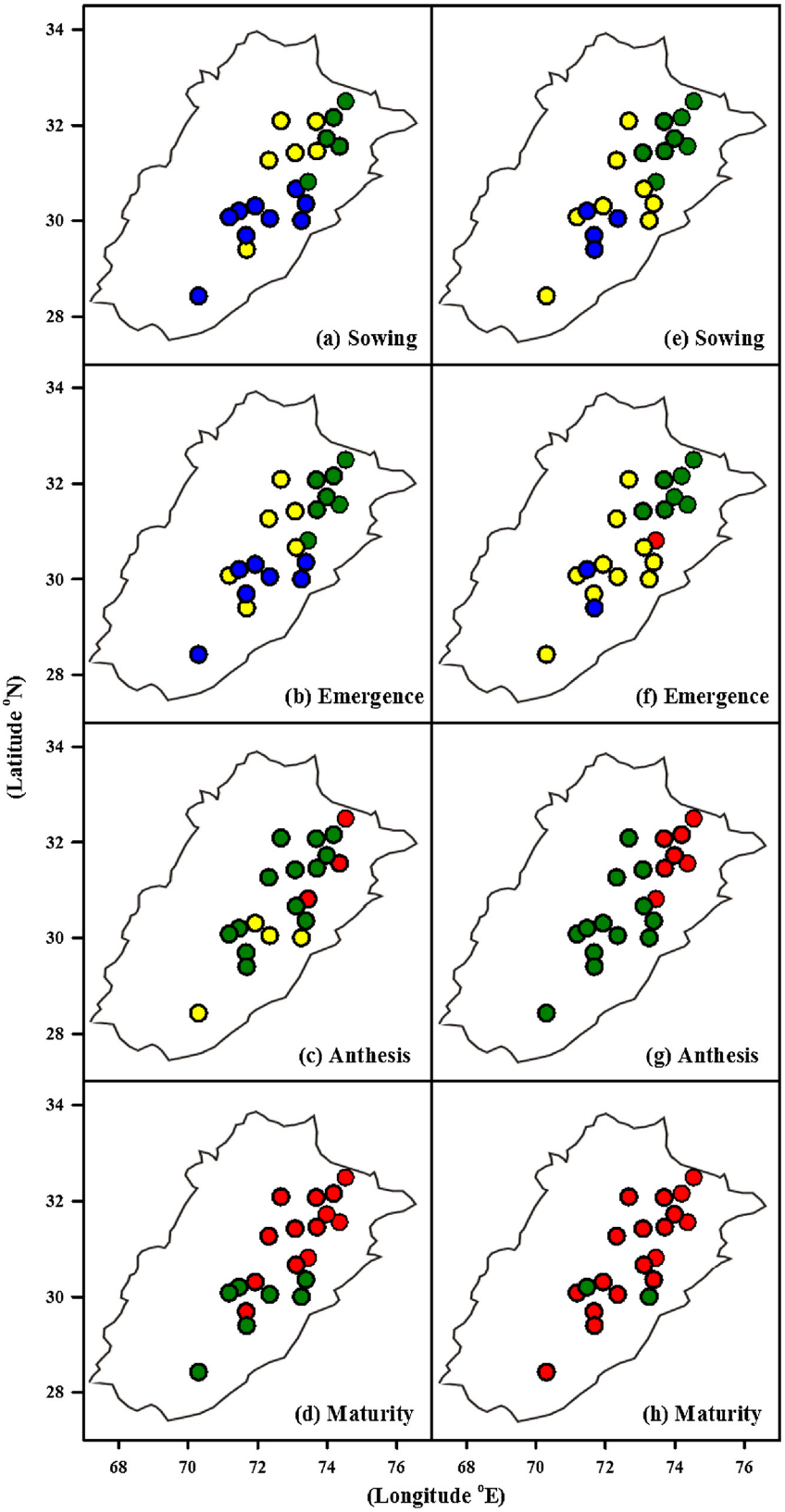

Fig. 4. Observed trends in phenology of spring season sunflower {sowing (a); emergence (b); anthesis (c); and maturity (d); circles with black borderline indicate statistical significant trends at p = 0.05 levels} from 1980 to 2016 in Punjab, Pakistan. Observed trends in phenology of autumn season sunflower {sowing (e); emergence (f); anthesis (g); and maturity (h); circles with black borderline indicate statistical significant trends at p = 0.05 levels} from 1980 to 2016 in Punjab, Pakistan.

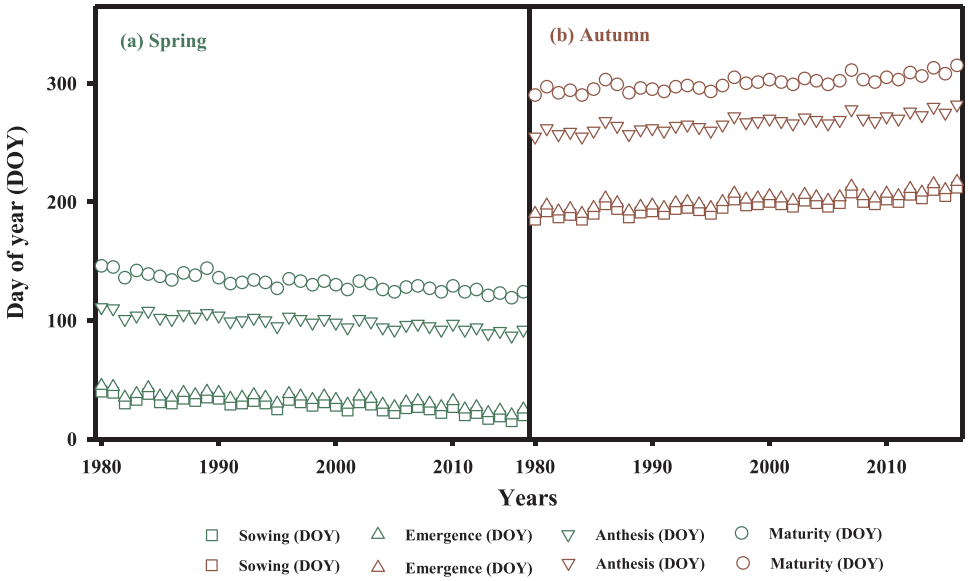

Fig. 5. Time series plots of farmer field observed dates of sowing, emergence, anthesis and maturity of spring (a) and autumn (b) season sunflower in Punjab, Pakistan.

for spring sunflower was reduced by 2.1 to 6.3 days decade^{-1} (statistically significant for 17 locations) with average of 4.4 days decade^{-1} and for fall sunflower reduced by 1.9 to 5.6 days decade^{-1} (statistically significant for 15 locations), having an average of 3.8 days decade^{-1}.

3.4. Trends for growing degree day requirements

The total number of growing degree days for sowing to anthesis for the spring hybrids increased from 65 to 99 °C d decade^{-1} (statistically significant for 14 locations), by a mean value of 80 °C d decade^{-1}, and for fall hybrids it ranged from 57 to 87 °C d decade^{-1}(statistically significant at 13 locations) with an average of 71 °C d decade^{-1}, (Fig. 7). Similarly, the total number of growing degree days from anthesis to maturity (reproductive phase) for spring hybrids was also increased, ranging from 74 to 106 d decade^{-1} (statistically significant for 16 locations) having an average of 91 °C d decade^{-1}, and for fall hybrids it ranged from 64 to 92 d decade^{-1} (statistically significant for 15 locations), with an average of 79 °C d decade^{-1}.

3.5. Temperature effect on observed phenology

There was a negative correlation between the spring sowing dates with temperature ranging from -1.5 to -4.2 days ºC^{-1} (statistically significant for 18 locations) with average of -3.0 days ºC^{-1} and for fall sunflower ranged from -1.1 to -3.3 days ºC^{-1} (statistically significant for 16 locations),having average value of -2.3 days ºC^{-1} (Table 3 and Fig. 8). There was also a negative correlation between the dates for spring with temperature ranging from -1.5 to -4.0 days ºC^{-1}(statistically significant for 17 locations) by an average of -2.8 days ºC^{-1} and for fall sunflower ranged from -1.0 to -3.2 days ºC^{-1} (statistically significant for 15 locations) having average of -2.2 days ºC^{-1}. Anthesis for spring sunflower was advanced, ranging from -0.8 to -2.9 days ºC^{-1} (statistically significant for 19 locations) having an average value of -1.7 days ºC^{-1} and for fall ranging from -0.6 to -1.8 days ºC^{-1} (statistically significant for 17 locations) with an average of -1.2 days ºC^{-1}. Physiological maturity of spring sunflower was negatively linked with temperature ranging from -0.4 to -1.9 days ºC^{-1} (statistically significant for 16 locations) with an average of -1.0 days ºC^{-1} and for fall sunflower ranging from -0.2 to -1.1 days ºC^{-1} (statistically significant for 16 locations) having an average value of -0.7 days ºC^{-1}. All phenological phases for spring and fall sunflower were negatively correlated with increasing temperature trend. Sowing to anthesis phase for spring sunflower was shortened from -0.7 to -2.0 days degree C^{-1} (statistically significant for 15 locations) with and average value of -1.3 days ºC^{-1} and for fall sunflower ranging from -0.4 to -1.5 days ºC^{-1} (statistically significant for 14 locations) having an average of -1.1 days ºC^{-1}. Sowing to maturity phase for spring sunflower was reduced ranging from -1.0 to -3.0 days ºC^{-1} (statistically significant for 18 locations) by an average of -2.1 °C^{-1} and for fall sunflower ranging from -0.7 to -2.3 days ºC^{-1} (statistically significant for 17 locations) with an average of -1.6 days ºC^{-1}. Anthesis to maturity phase for spring sunflower was advanced ranging from -0.4 to -1.1 days ºC^{-1} (statistically significant for 17 locations) by an average of -0.8 days ºC^{-1}, and for fall sunflower ranging from -0.2 to -0.9 days ºC^{-1} (statistically significant for 15 locations),having an average of -0.5 days ºC^{-1}.

3.6. Temperature effect on simulated phenology

There was a negative correlation between simulated phenology and temperature (Table 3). The simulated sowing to anthesis phase for spring was reduced ranging from -1.3 to -2.9 days ºC^{-1} (statistically significant at 19 locations) by an average of -2.0 days ºC^{-1} and for fall ranging from -1.0 to -2.4 days ºC^{-1} (statistically significant at 18 locations)with an average of -1.7 days ºC^{-1} (Fig. 8). Sowing to maturity phase for spring was reduced ranging from -1.8 to -4.7 days ºC^{-1} (statistically significant at 19 locations) by an average of -3.2 days ºC^{-1}, and for fall ranging from -1.3 to -3.9 days ºC^{-1} (statistically significant at 17 locations) with an average of -2.7 days ºC^{-1}. Reproductive phase (anthesis to maturity) of spring was also reduced ranging from -1.4 to -2.8 days ºC^{-1} (statistically significant at 18 locations) by an average of -1.8 days ºC^{-1} and for fall ranging from -1.0 to -1.7 days ºC^{-1} (statistically significant at 16 locations) with and average value of -1.4 days ºC^{-1}.

3.7. Observed plus simulated sunflower phenology

The sensitivity of the warming trend for the field-observed

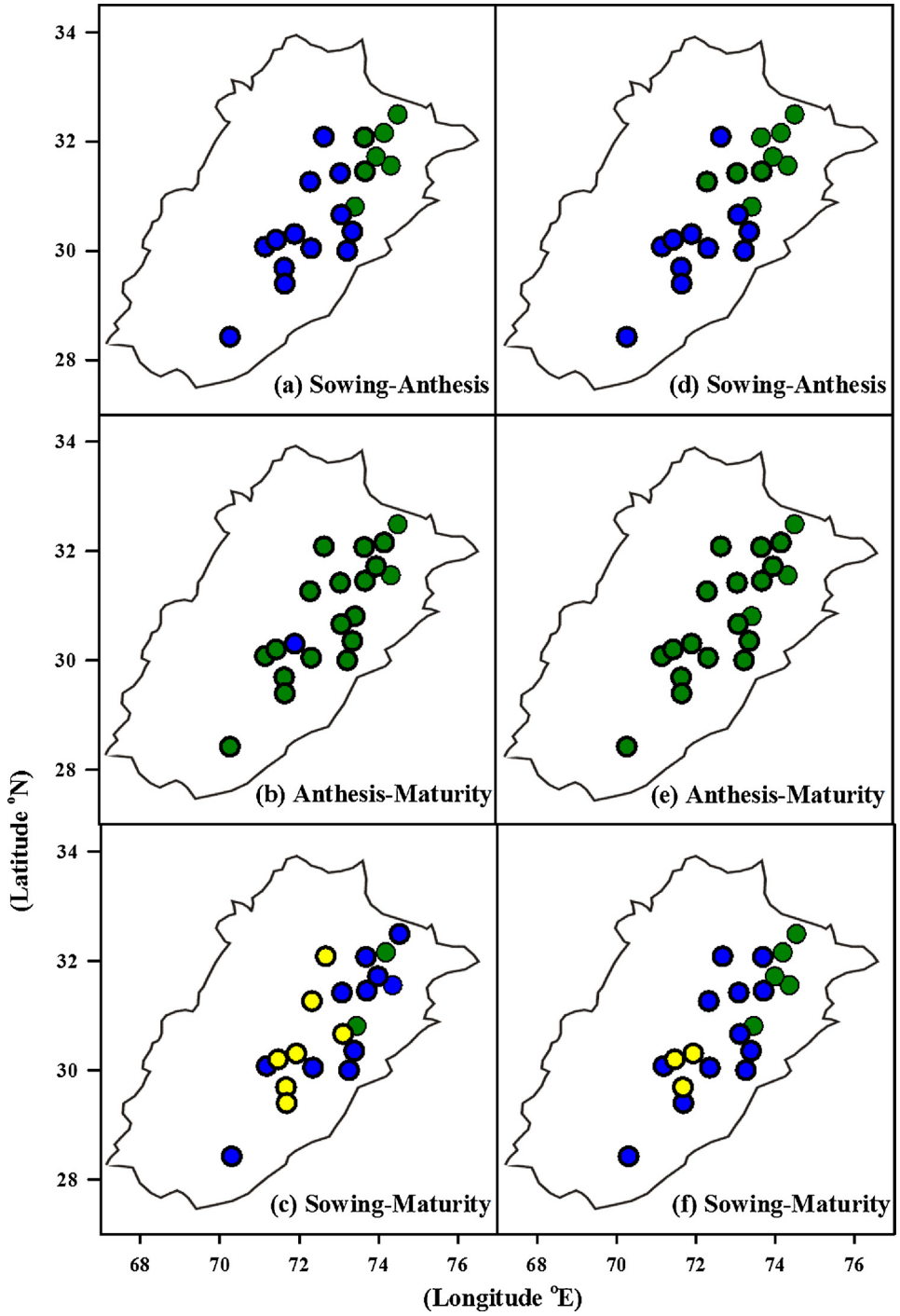

Fig. 6. Observed trends in phenology {(a, d) sowing-anthesis; (b, e) sowing-maturity and (c, f) anthesis to maturity; circles with black borderline indicate statistical significant trends at p = 0.05 levels} of spring (a, b and c; left) and autumn (d, e and f; right) season's sunflower from 1980 to 2016 in Punjab, Pakistan.

phenology was less compared to the model-simulated phenology. Average values of regression coefficients for the difference between field-observed and model-predicted data were statistically significant for spring and fall sunflower. The regression coefficient values for spring sunflower phases, i.e., sowing to anthesis, anthesis to maturity, and sowing to maturity were 0.7, 1.0 and 1.1 days $^{o}C^{-1}$ and for fall sunflower phases were 0.6, 0.9 and 1.1 days $^{o}C^{-1}$, respectively (Table 4). The differences between model-simulated and field-observed variations in phenology for varieties for spring and fall sunflower were noticeable, and various novel hybrids were introduced from 1980 to 2016 that had higher requirements for total growing degree days.

4. Discussion

Global warming has disrupted the phenology of many crops (He et al., 2015; Ahmad et al., 2017a,b; Abbas et al., 2017a,b). Because

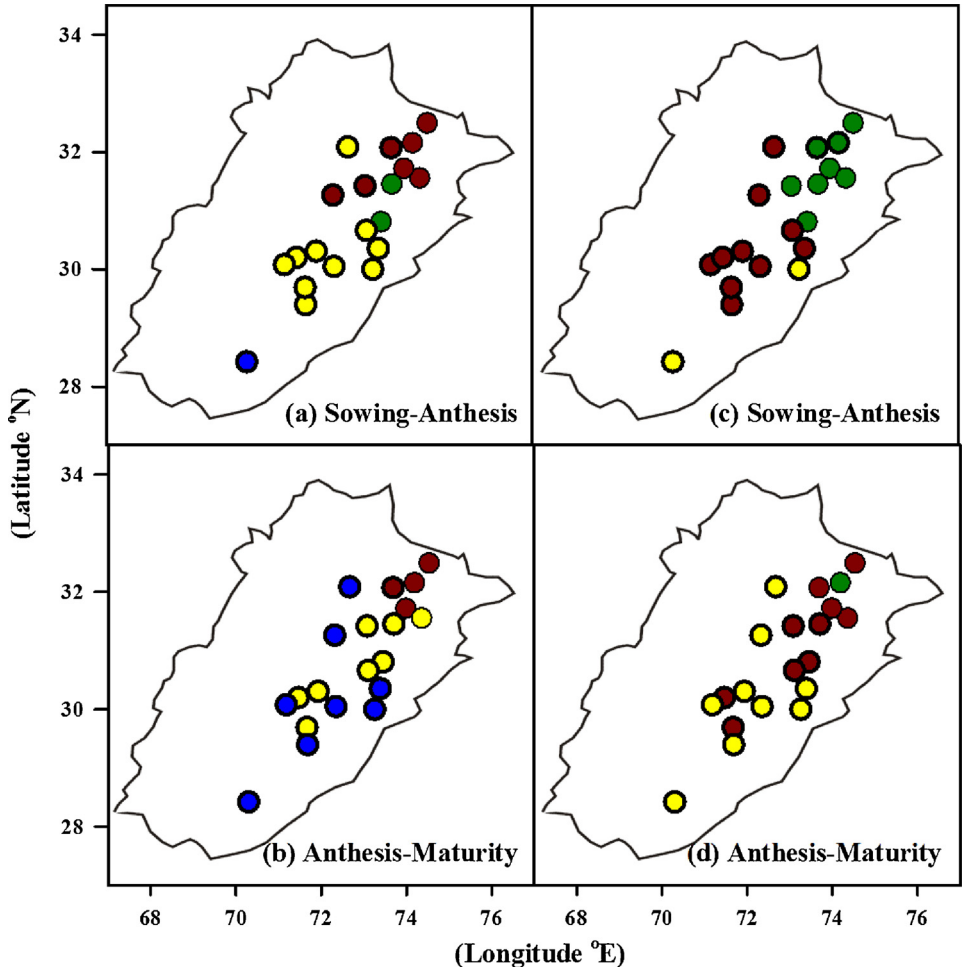

Fig. 7. Observed trends in thermal time required for spring (a, b; left) and autumn (c, d; right) season's sunflower from sowing-anthesis (a) and anthesis to maturity (b); circles with black borderline indicate statistical significant trends at p = 0.05 levels in Punjab, Pakistan.

phenology is mainly controlled by temperature (Hu et al., 2005; Cleland et al., 2007), the advancement in phenological metrics indicates that observed past temperatures were above the optimum to hasten the crop growth and development to early attain phenological stages (Kalyar et al., 2013; Abbas et al., 2017a,b). The changes in the observed phenological stages for the same hybrids across years exhibited an adaptation response to warming and indicate a positive sign that hybrids are adapting to climate warming. Human intervention such as changes in planting date and hybrid selection are also important for adaptation to climate warming. The changes in the planting schedule area reaction of the local farming community to cope the challenge the local change in temperature (Abbas et al., 2017a,b; Ahmad et al., 2017a,b). This study showed that sunflower planting occurs 3.0 days earlier with each 1 °C increase in temperature for spring and 2.3 days earlier with each 1 °C increase in temperature for fall sunflower (Table 3). The earlier shift in phenology will shorten the total growth season of the crop in the future with the current pace of rising temperature. The temperature-induced variability sunflower phenology that was found in this study confirms findings of other studies (Roetzer et al., 2000; Sparks et al., 2000; Abu-Asab et al., 2001; Fitter and Fitter, 2002; Williams and Abberton, 2004; Hu et al., 2005; Hatfield et al., 2011; Rani and Maragatham, 2013; He et al., 2015). These changes in phenology are important for the potential economic impact on final yield and determine the response to warming. Shorter growing season duration could be due to a later planting and early maturity, as found by Siebert and Ewert (2012), Zhang et al. (2013) and Moriondo et al. (2011). This reduction in the growing season duration has important biological implication because it determines the duration of food availability. Plant breeding plays a critical role in adjusting phenology for potential adaptation to the recent warming found in Punjab, Pakistan. In this study, we separated influence of introduced new hybrids in Punjab, Pakistan by simulating phenology of spring and fall sunflower using same hybrid for respective season during whole period with CSM-CROPGRO-Sunflower model. The phenology in the model simulation appeared to be more highly influenced by temperature than the observed data. The data in Table 4 show that introduction of new hybrids, i.e., Fh-331, Hysun-33, Hysun-39, and NK-274 with high growing degree days requirement from anthesis (A) to maturity (M) mitigated the adverse effects of warming by approximately 45% and 39% for spring and fall (Table 4). Other studies suggest that the introduction of hybrids is a successful tool among adaptation strategies for maize in China (Wang et al., 2011; Lin et al., 2017), maize in USA (Ma et al., 2017), grapevine in Portugal (Fraga et al., 2016), cotton in North China (Wang et al., 2017), and wheat in Loess Plateau, China (He et al., 2015).

Crop phenology is more likely to be influenced in the future by increasing temperatures that are expected to rise by 2–4 °C in the

Table 3
Summary of observed and simulated phenology response to temperature for spring and autumn sunflower in Punjab, Pakistan for 1980–2016.

Phenology	No. neg.[a]	No. pos.[b]	No. sig. neg.[c]	No. sig. pos.[d]	Reg. mean[e] (days $^{o}C^{-1}$)
Spring Stages (Observed)					
Sowing	20	0	18	0	-3.0
Emergence	20	0	17	0	-2.8
Anthesis	20	0	19	0	-1.7
Maturity	20	0	16	0	-1.0
Spring Phases (Observed)					
Sowing-Anthesis	20	0	15	0	-1.3
Anthesis-Maturity	20	0	17	0	-0.8
Sowing-Maturity	20	0	18	0	-2.1
Spring Phases (Simulated					
Sowing-Anthesis	20	0	19	0	-2.0
Anthesis-Maturity	20	0	18	0	-1.8
Sowing-Maturity	20	0	19	0	-3.2
Autumn Stages (Observed)					
Sowing	20	0	16	0	-2.3
Emergence	20	0	15	0	-2.2
Anthesis	20	0	17	0	-1.2
Maturity	20	0	16	0	-0.7
Autumn Phases (Observed)					
Sowing-Anthesis	20	0	14	0	-1.1
Anthesis-Maturity	20	0	15	0	-0.5
Sowing-Maturity	20	0	17	0	-1.6
Autumn Phases (Simulated)					
Sowing-Anthesis	20	0	18	0	-1.7
Anthesis-Maturity	20	0	16	0	-1.4
Sowing-Maturity	20	0	17	0	-2.7

[a] Number of locations with negative regression coefficients.
[b] Number of locations with positive regression coefficients.
[c] Number of locations with significant negative regression coefficients.
[d] Number of locations with significant positive regression coefficients.
[e] Mean of regression coefficients.

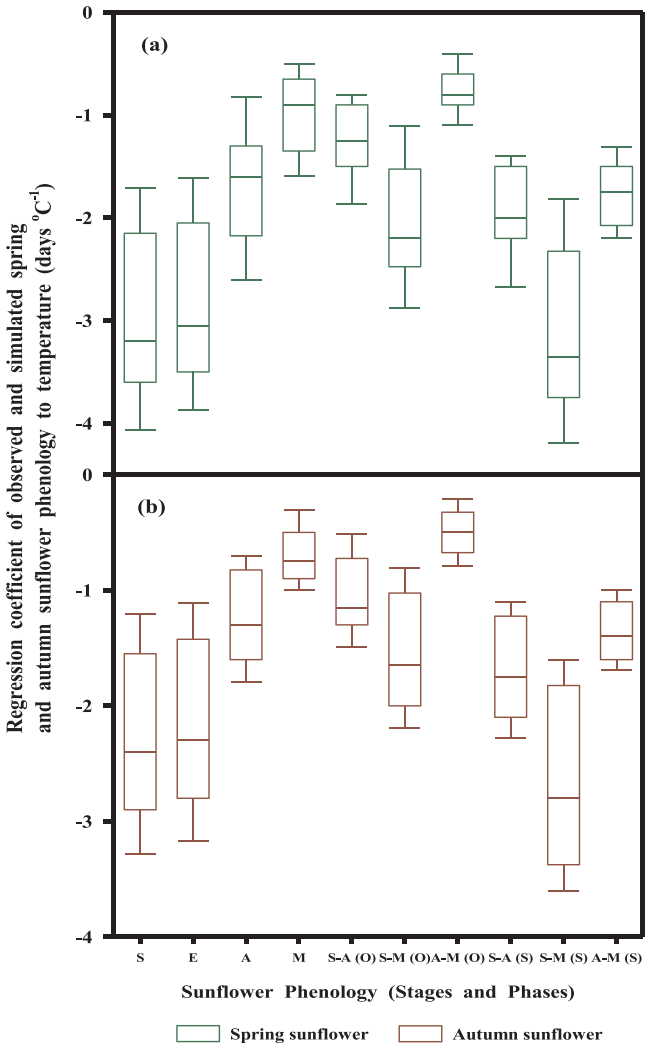

Fig. 8. Observed phenology (stages and phases) and simulated phenology (phases) versus temperature trends of spring (a) and autumn (b) sunflower cultivar at 20 location in Punjab, Pakistan from 1980 to 2016. (S: sowing; E: emergence; A: anthesis; M: maturity; S-A: sowing-anthesis; S-M: sowing-maturity; A-M: anthesis-maturity; O: observed; S: simulated). The central line represents median, box limits are 25th and 75th percentiles and whiskers represents the minimum and maximum values.

present century (Hatfield et al., 2011; Ahmad et al., 2015; He et al., 2015). The situation is alarming for arid and semi-arid regions like Punjab, Pakistan, especially given that the prevailing temperature is already beyond the physiological maximum. Hence, the development of new hybrids with higher growing degree days' requirement from anthesis to maturity is essential through breeding and adjusting sowing dates for sustainable sunflower production to mitigate global warming trends.

5. Conclusions

In the sunflower growing areas of Punjab, Pakistan, there has been a documented averaged increase in air temperature of 0.9 and 0.8 °C decade^{-1} for spring and fall season, respectively from 1980 to 2016 period. As a result of the increase in temperature trends, the main phenological stages of anthesis and maturity of sunflower for spring and fall season have advanced by averages of 3.8 and 3.1 days decade^{-1} and 2.2 and 1.8 days decade^{-1}, respectively, while periods of phenological phases sowing to anthesis, anthesis to maturity and sowing to maturity have decreased by averages of 2.8, 1.6 and 4.4 days decade^{-1} and 2.5, 1.2 and 3.8 days decade^{-1}, respectively. The negative effect of increases air temperature was to some extent mitigated through adaptation of new hybrids which had more growing degree day requirements. An estimated 45% and 39% of the increasing temperature impact on phenology for spring and fall sunflower was mitigated by adoption of the latest hybrids that had a higher growing degree days requirement for the critical phenological stages and phases.

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Table 4
Comparison of the responses of spring and autumn sunflower phenology with average temperature using the observed and simulated data in Punjab, Pakistan during 1980–2016.

Phenology	Regression coefficient (days $^{o}C^{-1}$)[a]				Difference between obs and sim. data (days$^{o}C^{-1}$).		t-Test (p-value)	
	Obs. data		Sim. data					
Phases	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn
Sowing-Anthesis	-1.3	-1.1	-2.0	-1.7	0.7	0.6	0.0094**	0.0057**
Anthesis-Maturity	-0.8	-0.5	-1.8	-1.4	1.0	0.9	0.0035**	0.0042**
Sowing-Maturity	-2.1	-1.6	-3.2	-2.7	1.1	1.1	0.0076**	0.0064**

Obs. = Observed; Sim. = Simulated.
[b]Duration of sowing to maturity.
[a] Mean of regression coefficients.
** Significant at the 0.01 probability level.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.03.015.

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